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CHEMICAL AND MINERAL RELATIONSHIPS IN IGNEOUS ROCKS.

THE attempt to correlate the mineral composition of igneous rocks with the chemical composition of their magmas, that is, of each rock as a whole, is rendered difficult by the chemical character of the rock-making minerals themselves, and by the fact that no fixed association of minerals necessarily results from the crystallization of an igneous rock magma, the association in a given case being affected to a greater or less extent by the physical conditions attending the solidification of the magma.

The pyrogenetic rock-making minerals are mostly silicates of several elements which may enter in different proportions into the composition of distinct minerals; so that the chemical difference between a number of these minerals lies in the proportions of their chemical components rather than in the kinds. Among the more important rock-making minerals, including the chief silicates, together with quartz and magnetite, there is no element found only in one mineral. Each constituent may enter several of them. Nevertheless there are limitations to the kinds of elements constituting certain minerals, as well as more or less definite proportions to their amounts in each case. But it is to be remembered that with the exception of quartz none of them has an absolutely fixed composition, but each belongs to an isomorphous or morphotropic series, that is, represents a more or less variable mixed salt or crystal. Variations in the chemical constituents of rock magmas will affect the chemical composition of several minerals in any case, as well as the relative proportions of all the minerals constituting the rock.

The relations between the minerals crystallized from a rock magma and the physical conditions attending its solidification have been scarcely more than recognized in a general way, though many examples have become well known. But enough has already been learned to warrant the conclusion that the attendant physical conditions exert a definite control over the grouping of the chemical elements in the molten magma, whereby the kind and character of the minerals crystallizing from it are affected. And it may be confidently predicted that careful comparison of the chemical composition of rocks with their exact mineral composition and texture, and with their mode of occurrence as geological bodies, will eventually lead to the discovery of these relationships.

Realizing the difficulties in the way of a complete correlation of the mineral and chemical composition of igneous rocks, and the limitations of our present knowledge both as to the relationships just mentioned, and as to the actual chemical composition of many rock-making minerals, it may still be possible to make a beginning of the correlation by attempting to state certain relationships between the theoretical molecules of the chief rock-making minerals and the chemical composition of igneous rock magmas.

Composition of the rock-making minerals.—Owing to the com plexity of even this preliminary correlation, it is advisable to consider only the more important rock-making minerals, leaving the less frequent ones for future elaboration of the discussion. The former may be grouped as follows: Quartz, the feldspathic minerals: the feldspars proper, with leucite, nephelite and the sodalites; muscovite, forming a link between feldspathoid minerals and ferromagnesian minerals; biotite and the other ferromagnesian minerals: olivines, pyroxenes, amphiboles; besides magnetite. Minerals necessary to a fuller discussion are melilite, garnet, titanite, perofskite, apatite, zircon, and others.

The chemical composition of each of these minerals, or groups of minerals, may be expressed in the simplest form, as in the following list, first by the empyrical formulas, second by the dualistic, the convenience of the latter being apparent when comparison is made with the chemical composition of the rocks, as expressed in the usual statement of analyses.

Quartz,	SiO_2	SiO_2
Orthoclase,	$KAlSi_3O_8$	$K_2O.Al_2O_3.6SiO_2$
Soda-orthoclase, Soda-microline,	$(K,Na)AlSi_3O_8$	$(K,Na)_2O.Al_2O_3.6SiO_2$
Albite,	$NaAlSi_3O_8$	$Na_2O.Al_2O_3.6SiO_2$
Oligoclase, Andesine, Labradorite,	$m\,(NaAlSi_3O_8)$ $n\,(CaAl_2Si_2O_8)$	
Anorthite,	$CaAl_2Si_2O_8$	$CaO.Al_2O_32SiO_2$
Leucite,	$KAlSi_2O_6$	$K_2O.Al_2O_3.4SiO_2$
Nephelite,	$KAlSi_2O_6$ $n\,(NaAlSiO_4)$	
Soda-nephelite,	$NaAlSiO_4$	$Na_2O.Al_2O_3.2SiO_2$
Sodalite,	$Na_4(AlCl)Al_2Si_3O_{12}$	$3[Na_2O.Al_2O_3.2SiO_2]+2NaCl$
Hauynite,	$Na_2Ca(NaSO_4.Al)Al_2Si_3O_{12}$	$3[Na_2O.Al_2O_3.2SiO_2]+2CaSO_4$
Nosite,	$Na_4(NaSO_4.Al)Al_2Si_3O_{12}$	$3[Na_2O.Al_2O_3.2SiO_3]+2NaSO_4$
Muscovite	$KH_2Al_3Si_3O_{12}$	$(K,H)_2O.Al_2O_3.2SiO_2$
Biotite,	$(H,K)_2(Mg,Fe)_2(Al,Fe)_2(SiO_4)_3$ or $2[(H,K)(Al,Fe)SiO_4]$ $(Mg,Fe)_2SiO_4$	$2[(H,K)_2O.(Al,Fe)_2O_3.2SiO_2]$ $2(Mg,Fe)O.SiO_2$
Olivine,	$(Mg,Fe)_2SiO_4$	$2(Mg,Fe)O.SiO_2$
Pyroxenes		
Enstatite,	$Mg_2Si_2O_6$	$MgO.SiO_2$
Hypersthene,	$(Mg,Fe)_2Si_2O_6$	$(Mg,Fe)O.SiO_2$
Diopside,	$CaMgSi_2O_6$	$CaO.MgO.2SiO_2$
Salite,	$Ca(Mg,Fe)Si_2O_6$	$CaO.(Mg,Fe)O.2SiO_2$
Augite,	$Ca(Mg,Fe)Si_2O_6$ $(Mg,Fe)(Al,Fe)_2SiO_6$	$CaO(Mg,Fe)O.2SiO_2$ $(Mg,Fe)O.(Al,Fe)_2O_3.SiO_2$
Acmite,	$NaFeSi_2O_6$	$Na_2O.Fe_2O_3,4SiO_2$
Amphiboles		
Hornblende,	$Ca(Mg,Fe)_3Si_4O_{12}$ $(Mg,Fe)_2(Al,Fe)_4Si_2O_{12}$ $Na_2,Al_2Si_4O_{12}$	$CaO.3(Mg,Fe)O.4SiO_2$ $(Mg,Fe)O.(Al,Fe)_2O_3.SiO_2$ $Na_2O.Al_2O_3.4SiO_2$
Arfvedsonite,	$(Na_2,Ca,Fe)_4Si_4O_{12}$ $(Ca,Mg)_2(Al,Fe)_4Si_2O_{12}$	$(Na_2,Ca,Fe)O.SiO_2$ $(Ca,Mg)O.(Al,Fe)_2O_3.SiO_2$
Riebeckite,	$Na_2Fe_2Si_4O_{12}$ $FeSiO_3$	$Na_2O.Fe_2O_3.4SiO_2$ $FeO.SiO_2$
Magnetite,	Fe_3O_4	

From this it will appear into how many different molecules any chemical element many enter. In order to simplify the problem further, the several kinds of molecules may be presented in the following manner:

Elements	Kinds of molecules		Kinds of minerals
K, Na, Al,	$(K,Na)_2O:AlO_3:SiO_2$ ::	1:1:6	orthoclase, albite
		1:1:4	leucite (amphibole)
		1:1:2	nephelite, sodalite(with excess of Na.)
	$(K,H)_2O:Al_2O_3:SiO_2$ ::	1:1:2	muscovite ($Al_2O_3 > K_2O$)
K, Na, Al, Fe,	$(K,H)_2O:(Al,Fe)_2O_3:SiO_2$ ::	1:1:2	mica (biotite)
Na, Fe,	$Na_2O:Fe_2O_3:SiO_2$ ::	1:1:4	acmite, riebeckite
Na, Fe, Ca,	$(Na_2,Ca,Fe)O.SiO_2$		arfvedsonite
Ca, Al,	$(CaO:Al_2O_3:SiO_2$ ::	1:1:2	anorthite
Ca, Mg, Fe,	$CaO.(Mg,Fe)O.2SiO_2$		pyroxene
	$CaO.3(Mg,Fe)O.4SiO_2$		amphibole
Mg, Fe,	$(Mg,Fe)O.SiO_2$		pyroxene
			olivine, mica
Mg, Fe, Al,	$(Mg,Fe)O.(Al,Fe)_2O_3.SiO_2$		pyroxene, amphibole

The alkalis combine with an equal number of molecules of alumina in the feldspathic minerals (except sodalites). These are polysilicates, metasilicates and orthosilicates; also in one of the amphibole molecules; while in muscovite part of the potassium is replaced by hydrogen. The alkalis with hydrogen enter into an orthosilicate, mica molecule with alumina and ferric oxide in the proportion of 1 : 1, the potash being generally less than alumina. Soda enters into a metasilicate molecule with ferric oxide, in the acmite molecule. It combines with lime and ferrous oxide in the metasilicate, arfvedsonite molecule. Calcium oxide enters an orthosilicate molecule with alumina in proportions of 1 : 1. — anorthite. Calcium occurs with magnesium and iron in metasilicate molecules in pyroxenes and amphiboles, which differ in the relative proportions of $CaO:(Mg, Fe)O$; in the first case in the ratio 1 : 1; in the second, 1 : 3. Magnesium and ferrous iron usually occur together in variable proportions, either in a metasilicate molecule with calcium in monoclinic pyroxenes and amphiboles, or without calcium in metasilicate molecules in orthorhombic pyroxenes, or in orthosilicate molecules in olivine and mica. They combine with aluminium and ferric iron in a subsilicate molecule in pyroxenes and amphiboles. Magnesium may occur without iron in metasilicate molecules, in diopside with calcium, and in enstatite without calcium. The alkali-alumina silicates may be polysilicates, metasilicates or orthosilicates. The ferromagnesian silicates may be metasilicates, orthosilicates or subsilicates. Iron may occur uncombined with silica in the form of magnetite, and silica may occur uncombined with other elements in the form of quartz or tridymite.

Preliminary correlation.— Some of the more evident relationships between the pyrogenetic minerals in igneous rocks and the chemical composition of the magma have been stated in a previous article in this volume.[1] They are : the usual occurrence of quartz with the polysilicate feldspars, and its non-occurrence with the meta- and orthosilicate feldspathic minerals : leucite, nephelite and sodalite; also the relation between these and the percentage of silica in the rock — the highest of these silicates always forming which is possible with the available silica in the magma. Another law seems to be that the alkalis control an equal amount of alumina, forming alkali-feldspathic molecules, and that aluminium in excess of this may combine with calcium to form anorthite molecules, or with magnesium and iron to enter pyroxene and amphibole molecules. Soda does not seem to unite with ferric oxide to enter pyroxenes or amphiboles in any considerable amount unless it is in excess of alumina. The metasilicate, orthorhombic pyroxenes, hypersthene and enstatite, usually occur in the more siliceous rocks instead of the orthosilicate, olivine, which usually occurs in the less siliceous rocks. But this is not an invariable rule, and olivine occasionally occurs in the more siliceous rocks (dacite) and not unfrequently in the presence of quartz. The orthosilicate, mica, commonly occurs in highly siliceous rocks together with quartz; pyrogenetic muscovite exclusively so. Biotite also occurs in rocks low in silica. Its range of occurrence bears no fixed relation to the percentage of silica in the rock. Magnetite occurs in rocks of all degrees of siliceousness and is not directly dependent on the amount of silica in the magma. It frequently occurs in association with quartz or tridymite. It is a general law that the ferromagnesian minerals become more abundant as the quartz and feldspathic minerals become less abundant.

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[1] On Rock Classification, JOUR. GEOL., Vol. VI, pp. 96–98.

A method of correlating the chemical and mineral composition of igneous rocks on a basis of the silica percentage and of the relative amounts of alkali in each case has been presented in the article in this volume[1] already cited. It is now proposed, without repeating what has been stated in that connection, to discuss in greater detail some of the relations between the mineral and chemical constituents of igneous rocks by making use of similar diagrams. In order to do this it will be necessary to start with the simplest assumptions, and those that appear to rest on the more general laws. Having obtained some of the simpler conceptions, more complex ones may be attempted with less danger of confusion.

It is possible to obtain an idea of the range of quartz and of leucite, nephelite and sodalite in igneous rocks by considering the most favorable cases for their occurrence, and afterwards the conditions that would modify their production. In order to render the discussion as simple as possible it is advisable to consider the extreme cases in which the alkali is either wholly soda or wholly potash. In Diagram 1 the black spots represent the rocks in which the soda is more than twice as great as potash, and the red spots those in which the potash is greater than soda. They correspond to the spots on Diagrams 2 and 4, Plates I and II of this volume. They are introduced to aid the imagination. The significance of the lines is explained in the text. For the phrase "the analysis or analyses of rocks" in the discussion of the diagrams the phrase "the rock or the rocks," will be substituted, it being understood that only the chemical attributes of the rocks are under discussion.

I. Let us first postulate the case of magmas whose *alkali is wholly soda*, and in which the *molecules of alumina are always in equal proportions to those of soda.* Then with no other constituent except varying percentages of silica the resulting rocks if wholly crystallized would consist of orthosilcate of sodium and aluminium, nephelite; this with polysilicate of the same elements, albite; albite alone; or albite and quartz, according as silica is lower or higher. We may say the rocks would lie on the curved line *QAN*. The point *Q* is where pure quartz occurs; and the point *A* where pure albite occurs; and *N* where soda-nephelite occurs. Pure albite rock would occur at *A*. Any rock on the line between *A* and *N* would consist of albite and soda-nephelite in proportions varying from one extreme to the other. Any rock on the line between *A* and *Q* would consist of albite and quartz in proportions varying in the same manner.

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[1] Loc. cit., pp. 98–103.

From *A* as a point of departure let us consider what must be the composition of soda-alumina rocks not occurring on the line *QAN*. If we consider magmas with constant alkali-silica ratios, namely .166, it is evident that proceeding from *A* horizontally, as the silica percentage becomes less, the soda and alumina must also become less, consequently the sum of these constituents will not be 100, which is always the total of the percentages in any case. There must therefore be other chemical constituents besides Na_2O, Al_2O_3 and SiO_2. The same is true if we proceed from *A* vertically downwards, that is, if we consider magmas having the same silica percentage, namely 68.7, for with decreasing alkali-silica ratios there will be less soda and alumina, and the sum of Na_2O, Al_2O_3, SiO_2 will not be 100. The same will be true if we proceed in any direction from *A* below the line *QAN*.

All rocks except those occurring upon this line must contain other constituents than Na_2O, Al_2O_3, SiO_2. These may be CaO, MgO, FeO, Fe_2O_3 (potash being excluded by the initial assumption). Let us assume them to be either CaO, MgO, FeO, singly or together, and that they occur as silicates. The case of $FeO.Fe_2O_3$, magnetite, will be considered subsequently. It having been assumed that alumina is present only in proportions to satisfy soda, the possibility of the formation of an aluminous molecule with these constituents will be excluded for the present. The silicates capable of forming from CaO, MgO and FeO are orthosilicates and metasilicates; olivine, $2(Mg,Fe)O.SiO_2$, with its theoretically possible extremes $2FeO.SiO_2$ (fayalite) and $2MgO.SiO_2$ (fosterite); orthorhombic pyroxenes, enstatite, $MgO.SiO_2$, and hypersthene, $(Mg,Fe)O.SiO_2$, and the monoclinic pyroxenes, diopside, $CaO.MgO.2SiO_2$, and salite, $CaO.(Mg,Fe)O.2SiO_2$. It is possible to introduce into the composition of a magma such as already postulated one or more of these molecules in such proportions as to make the sum of all equal to 100. But it is clear that the development of a silicate of any of these kinds in the magma would affect the distribution of the silica among the other molecules, that is, it would affect the relative porportions of albite and nephelite or of albite and quartz. It is possible to discover by simple algebra what would be the range of percentages of silica and the range of the alkali-silica ratio for a series of rocks composed wholly of albite and any one of the calcium, iron, magnesium molecules just mentioned. This range will be expressed by a curved line on the diagram extending from the point *A* to the point corresponding to the locus in the diagram of the pure molecule under consideration. Several of these lines are indicated on Diagram 1. The most extreme case, most favorable to the presence of albite is that in which it occurs in combination with $2FeO.SiO_2$, orthosilicate of iron. The range is indicated by line *AFa*, which shows the alkali-silica ratios necessary in order that a rock should consist wholly of albite and Fe_2SiO_4. Any rock occurring above this line and containing only the constituents $Na_2O = Al_2O_3$, FeO, SiO_2 would have relatively too little silica to form albite out of all the soda and alumina and would contain some nephelite. That is, all rocks of this kind occurring above the line *AFa* would carry nephelite, even those having alkali-silica ratio $=.03$, if $SiO_2 = 31$. Conversely, all rocks occurring below this line would have relatively too much silica to convert all the soda and alumina into albite and there would necessarily be quartz, if FeO alone formed an orthosilicate, which is the case in hand. Quartz would thus be a necessity in rocks with only 35 per cent of SiO_2 when the alkali-silica ratio is less than .045. For a combination of albite and $2MgO.SiO_2$ the range is shown by the line *AFo*, and for a combination of albite and olivine, $2(Mg,Fe)O.SiO_2$, in which Mg: Fe :: 3: 1, the range is *AOl*. From this it is seen that if orthosilicate of magnesium accompanies that of iron the nephelite limit will advance toward the left, that is, in the direction of higher silica percentages, and the quartz limit will recede in the same direction.

In case iron and calcium or magnesium occur as metasilicates the range of possible combinations of these with albite is shown by the lines *AF*, *AC*, *AM*. If magnesium and iron occur together in equal proportions, as in some hypersthene, the line nearly coincides with *AC*. So also if the metasilicate has the composition $CaMgFeSi_3O_9$, or $Ca_2MgFeSi_4O_{12}$ (a diopside) or $Ca_2Fe_3Mg_3Si_8O_{24}$ (actinolite molecule in amphibole) the range would coincide with the same line. An increase of magnesium would move the line to the left toward *AM*. The range of positions for diopside is indicated by the bracket in the diagram. The range of positions for enstatite would lie to the left of this for the most part. From this it appears that rocks having soda and alumina in equal amounts together with metasilicates of iron, magnesium and calcium, if they occur to the right of the limits just described would necessarily contain nephelite, and if they occur to the left of these limits they must contain quartz. Since metasilicates are the highest silicate of these elements occurring in igneous rocks it follows that no other ferromagnesian molecule may be postulated which will appropriate more silica from the magma. Hence the most favorable case, namely that involving the highest silicate of alkali and alumina and the highest of calcium, iron, and magnesium, requires the presence of quartz in all holocrystalline rocks occurring to the left of these lines. In actual fact the three elements just named usually occur in somewhat similar proportions, so that the position of the line *AC* represents the limit of quartz in the ordinary case most favorable to its scarcity. Any combination of orthosilicate will tend to move the quartz limit still further toward the right, in the direction of lower silica percentages. Quartz must therefore occur in rocks with lower and lower silica in proportion as the alkali-silica ratio decreases, and as lower silicate molecules are developed instead of higher silicates. The line *AC* is probably very near the highest limit of *no quartz* to be found in holocrystalline igenous rocks.

If any of the iron crystallizes as magnetite instead of combining with silica to form ortho- or metasilicates, silica will be liberated to form more albite out of nephelite, or to produce more quartz by the side of albite. The effect of the development of magnetite then is to shift the quartz-nephelite limit farther to the right, that is, toward lower silica percentages. In the case of rocks within the nephelite limit, the effect will be to decrease the nephelite and increase the albite. It may also react upon the ferromagnesian silicates when orthosilicates are present, permitting the liberated silica to convert some of the orthosilicates into metasilicates without materially affecting the relative proportions of the other constituent minerals.

In this connection attention may be called to the line *NFa*, which is the range of magmas composed wholly of nephelite and the orthosilicate of iron. It appears to be the limit toward which the highly sodic magmas tend, as may be seen in Diagram 1. Magmas low in alkalis associated with the eruptive iron ores lie beyond this boundary.

II. In order to discover the relations that would obtain for magmas in which *the alkali is wholly potash* when *alumina is present in amounts just equal to the potash*, we have to consider the range of positions for rocks corresponding to mixtures of quartz and orthoclase (potassium-aluminium polysilicate), and of orthoclase and leucite (potassium-aluminium metasilicate). This corresponds to the red line *QOL*. As already remarked in the previous paper, the lowest potassium-aluminium silicate among the feldspathoid minerals appears to be the metasilicate, leucite, and when potassium is found in rock-making nephelite it may be explained as in a metasilicate molecule mixed with the sodium-aluminium orthosilicate. If we conduct the discussion in the same manner as in the previous case we should proceed from the point *O*, the position for a pure potash-orthoclase rock. At this point the alkali silica ratio =.166 and $SiO_2=64.7$. Rocks consisting of pure orthoclase and leucite will occur along the line *OL;* those composed of pure orthoclase and quartz along the line *OQ*. Rocks having an alkali-silica ratio of .166 and less than 64.7 per cent. of silica must contain some other constituents than $K_2O=Al_2O_3$ and SiO_2. The same is true for all rocks lying below the line *QOL*. The range of rocks that might consist of pure orthoclase and orthosilicate of iron is shown by the red line *OFa*, close to the corresponding line for soda magmas. All rocks occurring above this would necessarily contain leucite, all below it would contain quartz. The lines *OOl* and *OFo* represent the range for rocks consisting respectively of orthoclase and olivine, and of orthoclase and orthosilicate of magnesium. They also mark the limit of the quartz-bearing rocks of this kind on one side, and of leucite rocks on the other. The lines for rocks composed of orthoclase and metasilicates of iron, magnesium and calcium are *OF*, *OC*, *OM*. They are somewhat further from the corresponding ones for soda magmas than in the case of the orthosilicates. Comparing their positions with those of the corresponding lines for soda magmas, it is seen that the quartz limit is lower in the scale of silica percentages for potash magmas than for soda magmas. That is, other things being equal, quartz will occur in less siliceous potash rocks than in the corresponding soda rocks, the most marked differences being in rocks highest in alkalis.

The development of magnetite would have the same effect in shifting the quartz-leucite limits toward the right, that is, toward rocks with lower silica percentages as in the case of soda magmas. The line *LFa* is the range for magmas composed of leucite and orthosilicate of iron and seems to be the lowest limit for potash magmas, as stated on page 102 of this volume.

Magmas in which both soda and potash occur with equal amounts of alumina would behave in a manner analagous to that just described for either extreme, the feldspars would be soda-potash polysilicates, with quartz or with leucite or nephelite. The lines indicating the range of combinations of feldspar and ferromagnesian silicates would occupy positions intermediate between the corresponding lines for albite and for orthoclase. The quartz-leucite-nephelite limits would be nearly the same as before.

III. Let us now postulate the case of magmas in which the *alkalis control an equal amount of alumina* and in which *lime and additional alumina occur in the proportion of one to one* and *constitute orthosilicate, anorthite molecules.* First, let all of the alkali be soda. This case is illustrated by Diagram 2. As the relative proportions of the constituents, $Na_2O=(Al_2O_3)'$, $CaO=(Al_2O_3)''$ and SiO_2 vary, those rocks in which there is soda and no lime will consist of albite and quartz, or of albite and nephelite, and will occur along the line *QAN*, Diagram 2, as in the previous Diagram 1. All rocks occurring below this line will contain anorthite molecules in variable proportions. Pure anorthite rock will occur at the point *An*, where the alkali-silica ratio $=0$, and $SiO_2=43.2$. The range of rocks composed wholly of albite and anorthite in varying proportions will occur along the line *AAn*. They correspond to rocks each consisting of a feldspar of the albite-anorthite series. The points on this line at which particular mixtures occur, such as Ab_6An_1, $Ab_2\ An_1$, etc., are designated in the diagram. This line also indicates the range of rocks consisting wholly of soda-lime-feldspar. All rocks from magmas of this case, III, to the right of this line must contain nephelite in addition to these feldspars. All rocks to the left must contain quartz, the argument being the same as for magmas of cases I and II. Assuming that the feldspar present is always one corresponding to the particular combination of albite and anorthite molecules in the magma, we may discover the range of magmas consisting of combinations of each of these kinds of feldspar and quartz on the one hand, and of these and nephelite on the other. They are indicated by the lines *QA*, *Qb*, . . *QAn* and *NA*, *Nb*, . . *NAn*, which also indicate the limits for magmas of this kind. None would be possible to the right of the line *NAn*, unless containing other elements than those already mentioned for this case, III.

Since within the boundaries *QNAn*, rocks may exist composed wholly of quartz and the feldspathic minerals mentioned, the presence of any ferromagnesian compound necessitates the diminution of some of the first-named constituents, and since the silica percentages and alkali-silica ratios are the coördinates by which comparisons are made, we may assume that the presence of ferromagnesian constituents affects the lime and its equivalent alumina. Let them be affected equally. The orthosilicate anorthite molecules may then be replaced in some uniform manner by non-aluminous ferromagnesian orthosilicates or metasilicates. If the anorthite molecules be replaced by orthosilicate of iron, Fe_2SiO_4, the varying results are indicated in Diagram 2. If wholly replaced by Fe_2SiO_4, the line *AFa* would represent the range of the resulting rocks composed of varying proportions of albite and Fe_2SiO_4. And the area *AFaAn* would be the range of rocks composed of varying proportions of albite and Fe_2SiO_4 and anorthite. The lines *bFa*, *cFa*, etc., indicate the ranges of rocks composed of Fe_2SiO_4 and Ab_6An_1, Fe_2SiO_4 and Ab_2An_1, etc. That is, ranges in which the character of the lime-soda feldspar is constant, but the proportions of Fe_2SiO_4 vary. The line *Ay* shows the range of rocks composed of albite, with varying amounts of anorthite and Fe_2SiO_4 in the proportion of 4 to 3. At the points *b'*, *c'*, *d'*, etc., where this line intersects the lines *bFa*, etc., the rocks would consist of Fe_2SiO_4 and the feldspars Ab_6An_1, Ab_2An_1, etc. From this it is evident that as the molecules of anorthite are replaced by ferromagnesian molecules, the feldspars in a rock of any given silica percentage and alkali-silica ratio become relatively higher in albite molecules, that is, the lines *Ob*, *Oc*, etc., would shift farther from *QA;* more sodic feldspars would occur in rocks with lower alkali-silica ratios. There would be a similar movement of the lines *Nb*, *Nc*, etc., away from *NA;* more sodic feldspars would be found in rocks lower in silica.

If the anorthite molecules be replaced by orthosilicates of iron, or of iron and magnesium, less silica would be required than before, and the quartz limit would shift to the right. If they were replaced by metasilicates of iron, magnesium or calcium, more silica would be required, and the quartz limit would shift to the left. If both were developed together the quartz limit might remain nearly as before. If magnetite were developed the effect on the quartz limit would be still more marked, and it would be shifted still farther in the direction of lower silica percentages.

Second, let all of the alkali be potash. Assuming that in this case there would be two distinct kinds of feldspar present, potash-orthoclase and anorthite, the range of rocks consisting wholly of these two minerals in variable proportions would lie along the red line *OAn*, Diagram 3, and the line *QOL* would be the range of rocks of this kind free from anorthite. All rocks of this kind occurring to the right of the line *OAn* must contain leucite; all those to the left must contain quartz. The effect of replacing anorthite molecules by ferromagnesian molecules would be similar to that just stated for the albite-anorthite magmas; however, orthoclase not being combined with anorthite, would remain as before except where changes in the silica affected the orthoclase molecules by reducing them to leucite. or affected the leucite molecules by raising them to orthoclase. This would occur in the neighborhood of the line *OAn.*

Third, if soda and potash were both present, other things being the same as postulated in the general statement of case III, it is evident that the range of rocks that might consist wholly of feldspars, either pure albite, pure orthoclase, or pure anorthite, or any possible mixture of these, would be within the area *AOAn*, Diagram 3. This narrow area would be the boundary between the quartz range on one side and the leucite-nephelite range on the other. The effect on the albite-anorthite feldspar, whose character would be that previously indicated if all the alkali were soda, by the partial replacement of soda by potash would be to render it lower in the scale toward the anorthite end, so that the amount of orthoclase would be increased and the accompanying lime-soda-feldspar would be more calcic. This is indicated in Diagram 3. As potash replaces soda, the extreme limit of pure alkali-alumina silicate would shift along the line *NL* toward *L*. When they are in equal amounts the limit would be at *P*. At the same time, the range of rocks consisting wholly of anorthite, with albite and orthoclase in equal proportions, would be indicated by the line *xAn*. The points b', c', d', etc., on it are where the lime-soda feldspar would have the value of Ab_6An_1, Ab_2An_1, Ab_1An_1, etc. The red lines connecting these points with *P* on one side and with *Q* on the other represent the range of rocks composed wholly of these particular lime-soda feldspars and leucite-nephelite on the one hand, and of these feldspars and quartz on the other. The replacement of anorthite molecules by ferromagnesian ones will have the same effect as that just stated for each extreme of alkali-lime-feldspar magmas.

IV. There remains to be discussed the modifications that would be effected in the feldspathic magmas already postulated by the introduction of ferroaluminous molecules. These may be of two kinds: ferromagnesian-ferroaluminous molecules, appearing in pyroxenes and amphiboles, with the general formula $(Mg,Fe)(Al,Fe)_2SiO_6$; and alkali-ferroaluminous molecules, occurring in mica, amphiboles, and pyroxene. Among these are molecules free from ferric iron, and others free from aluminium. They are $KH_2Al_3Si_3O_{12}$, $(K,H)(Al,Fe)SiO_4$, $NaAlSi_2O_6$, $NaFeSi_2O_6$.

Let us first consider those free from alkalis. Upon the general assumption that the alkalis control an equal amount of alumina, the introduction of ferromagnesian-ferroaluminous molecules would demand an increase in the alumina over that necessary to satisfy the alkalis. This must take place at the expense of the ferromagnesian and calcium molecules in cases I and II, or at the expense of anorthite molecules, in case III.

Let us consider cases I and II. The molecule $(Mg,Fe)(Al,Fe)_2SiO_6$ is a subsilicate. The range of silica percentages for all manner of variations in its composition is from 29.52 for $MgAl_2SiO_6$ to 20.54 for $FeFe_2SiO_6$. The molecule usually is more nearly the average of these extremes. The silica range is indicated in Diagram 1 by the bracket, which shows that this molecule requires less silica than the orthosilicate of iron, considerably less than olivine, and very much less than diopside or enstatite. Its development, then, would extend the quartz limit and reduce the nephelite-leucite limit very considerably in proportion to its own amount. It may be stated that in general its amount is quite subordinate to that of the ferromagnesian ortho- and metasilicates. Its effect on magmas of case III, where anorthite occurs, would be of the same kind as the introduction of non-aluminous ferromagnesian silicates, but the degree of the change would be greater in proportion to the number of molecules introduced.

Turning to the alkali-ferroaluminous molecules, it is to be observed that one, $(K,H)(Al,Fe)SiO_4$, is well known to be capable of appearing in igneous rocks of almost any chemical composition in which its elements occur. Two others $(K,H)AlSiO_4$, and $NaFeSi_2O_6$ appear to occur in rocks with special chemical composition, while the fourth, $NaAlSi_2O_6$, is less well known but may be supposed to be of wide occurrence in small amounts. The first belongs to biotite. If the ratio between potassium and hydrogen varies from 1 : 1 to 1 : 2, and the aluminium and iron be supposed to reach their possible extremes, from normal biotite to lepidomelane, the range in silica percentage for this orthosilicate molecule would be from 29.07 to 19.10, which is indicated by the bracket in Diagram 1. The relative proportions of potash and alumina vary from 1 : 1 to 1 : 2 in most instances. Sodium does not enter into the molecule to any considerable extent, the development of biotite then affects the potash-feldspathic molecules. In orthoclase rocks within the quartz limit its development would reduce the amount of orthoclase molecules, and would change a polysilicate into an orthosilicate and liberate silica, increasing the amount of quartz or raising ferromagnesian orthosilicates to metasilicates. But the development of biotite would draw upon the ferromagnesian orthosilicate (Mg,Fe) SiO_3, reducing the amount that might be converted into metasilicate. The quartz limit would then be shifted toward lower silica percentages. In orthoclase-leucite rocks, or leucite rocks without orthoclase, the development of this potash-ferroaluminous molecule would reduce the amount of these minerals and liberate silica, which would raise the metasilicate leucite to orthoclase. The effect would thus be to cause the leucite limit to recede toward lower silica percentage.

It has already been noted that the development of biotite involves, besides the potash-bearing molecule under discussion, an orthosilicate of iron and magnesium, which is the same as an olivine molecule. The development of this molecule in rocks that might otherwise carry ferromagnesian metasilicate molecules would still further liberate silica, to appear as more quartz or raise more leucite to orthoclase.

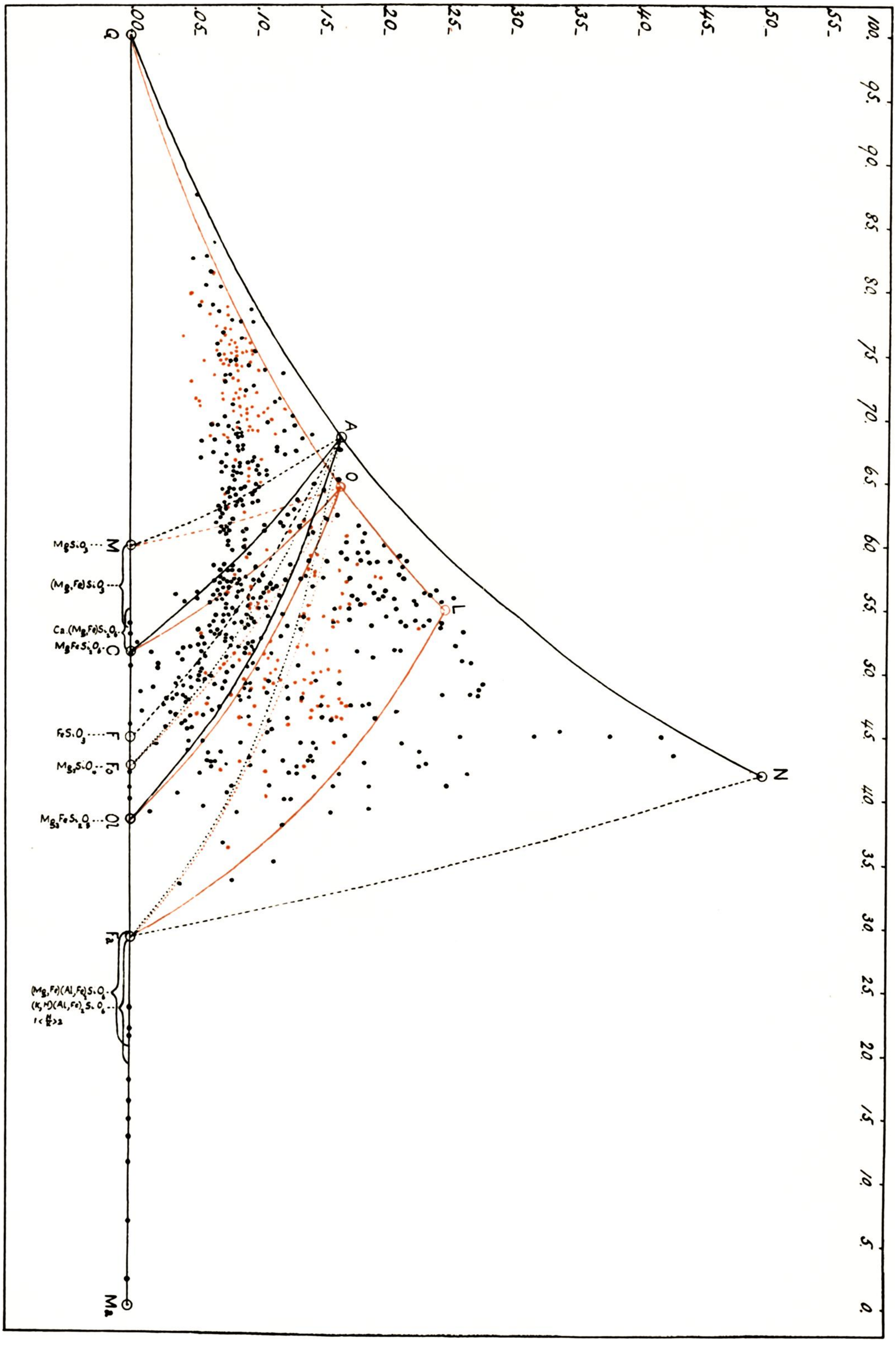
In case alumina is in excess of potash in this mica molecule the excess of alumina must be drawn from an excess of alumina over the alkalis originally in the rock, or it must be drawn from a sodium-aluminium molecule, since no potash molecule, in which potash exceeds alumina, occurs to any extent in the pyrogenetic minerals according to present theories. In the second instance the effect would be to reduce the albite or nephelite molecules and drive the soda into combination with ferric iron, affecting the distribution of the silica.

The development of the metasilicate molecule, $NaAlSi_2O_6$, which enters amphibole, would reduce the albite molecules with the liberation of silica and the possible production of quartz, or the raising of nephelite to albite. It would reduce the nephelite molecules if it did not affect those of albite, and would require additional silica, which would have to be drawn from a polysilicate (orthoclase) or from a metasilicate. It does not appear to enter largely into the composition of rock-making amphiboles, except possibly into those crystallized from magmas rich in soda and alumina.

The molecule $(H,K) Al Si O_4$, with little or no iron and with hydrogen and potassium, usually in the proportion of 2:1, occurs as muscovite. It is nearly identical with that occurring in biotite, except for lower iron. Muscovite occurs as a pyrogenetic mineral only in the most highly siliceous and quartzose rocks, where it is sometimes accompanied simply by quartz and alkali feldspar. The fact that this molecule often carries three times as much alumina as potash, and the absence of other potash molecules in which potash occurs in greater amount than alumina, indicates that the muscovite molecule develops in magmas in which alumina is in excess of the alkalis. Its presence bears no direct relation to the percentage of silica in the rock. Its absence from many rocks in which alumina is in excess of alkalis is probably due to its combination with iron and magnesia, resulting in the formation of biotite. Magmas sometimes occur with so large an excess of alumina that it crystallizes as corundum, Al_2O_3, in association with alkali-feldspars. The alumina in these cases did not enter muscovite molecules with the potash.

The development of the sodium-iron-metasilicate, $Na Fe Si_2 O_6$, which occurs in pyroxene, as the acmite molecule, and also in riebeckite, is pronounced in magmas rich in sodium and ferric iron; Fe_2O_3 appearing to take the place of Al_2O_3. Considered in connection with the composition of rocks of case I and III, Diagrams 1 and 2, its presence reduces the amount of albite, and increases the silica available for quartz or for raising nephelite molecules to albite according to the position of the rock in the scheme. Its presence would therefore shift the quartz limit toward lower silica percentages. It does not appear to play any considerable rôle in rocks low in soda or in ferric oxide.

It is not the plan of the present paper to discuss the effect on the mineral composition of rocks of the development of the less abundant or subordinate minerals. In some cases their production is clearly due to the presence of special elements,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$(Mg,Fe)SiO_3$
$Ca.(Mg,Fe)Si_2O_6$
$MgFeSi_2O_6$ · C
$FeSiO_3$ ···· F
Mg_2SiO_4 ·· Fo
$Mg_3FeSi_2O_8$ ··· Ol
Fa
$(Mg,Fe)(Al,Fe)_2SiO_6$
$(K,H)(Al,Fe)_2SiO_6$
$1 < \frac{H}{K} > 2$
Ma

DIAGRAM I.

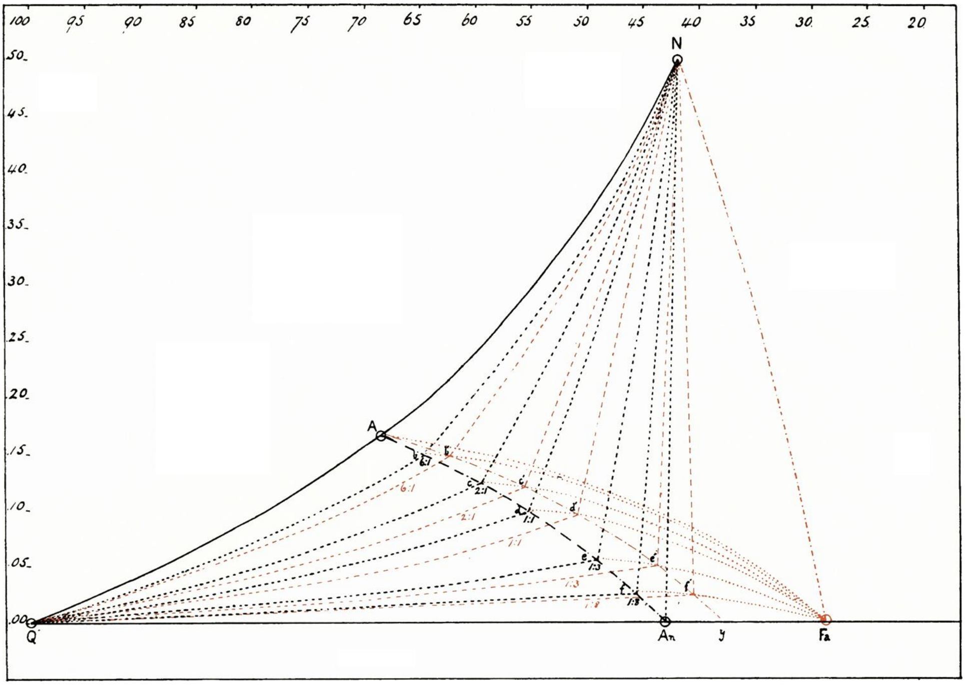

DIAGRAM 2

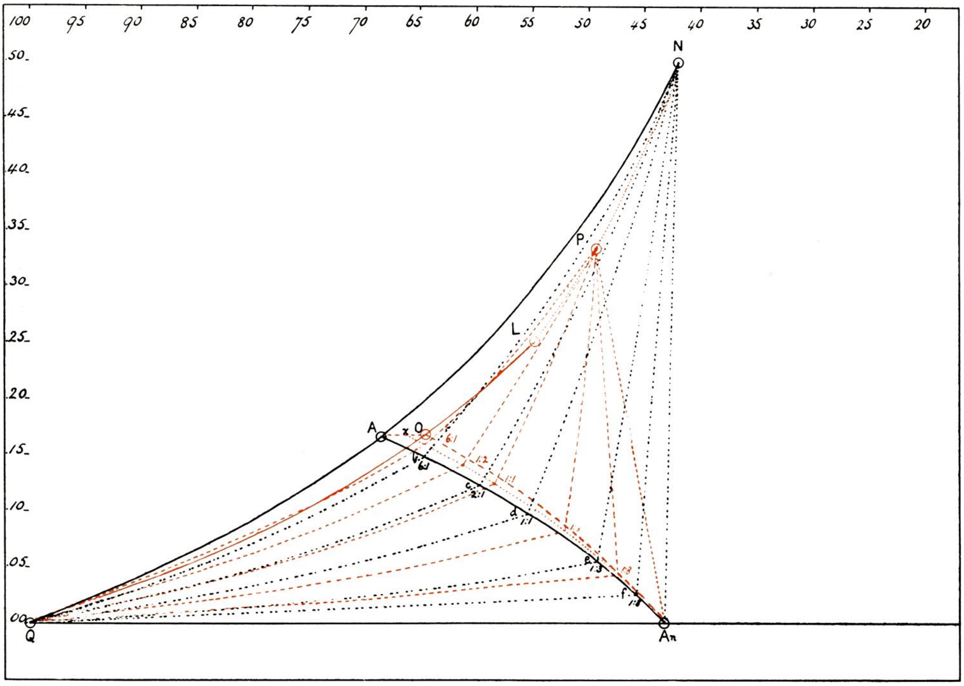

DIAGRAM 3

such as phosphorus, titanium, zirconium, sulphur, chlorine, fluorine, boron, etc., and their influence in modifying the proportions of the preponderant minerals is self-evident.

The discussion has been far from complete, but it is hoped that it may lead to a better understanding of the relations between the chemical and mineral composition of igneous rocks, especially the factors controlling the range of quartz on the one hand and of leucite and nephelite on the other. It certainly makes more evident the interdependence of the various minerals on one another and on the chemical composition of the magma. And it may possibly suggest lines of investigation that may contribute more substantially to our knowledge and conception of these intricate relationships. JOSEPH P. IDDINGS.